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Strategic structure of the North-East Arctic cod fishery: the effect of climate change

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Preface

This master's thesis for the programme in Economics written by Magnus Tvedt Willadssen has been supervised by Florian K. Diekert.

Summary

This thesis explores the consequences that climate change could have for the North-East Arctic cod fishery shared by Norway and Russia. The focus is on the competitive equilibrium. Today, the mature cod migrate to the Norwegian coast to spawn each year. I will assume that higher ocean temperatures leads to new spawning areas being established in Russian waters. This would mean that Russia gets increased access to the mature age class. The effect this has on Norway is, as this thesis will show, not entirely clear. The direct effect of reduced access to the mature stock will make Norway worse off, but the Russian reaction to this change will likely have the opposite effect.

The problem is explored by modeling the fishery as a game between Norway and Russia where each agent decides how much to harvest of mature and immature fish based on how much the other agent is harvesting. Using a version of the model of Levhari and Mirman (1980) modfied to include two age classes rather than just one, I derive both the first best allocation and the Nash equilibrium for the competitive case. The first best solution is very similar to that found by Levhari and Mirman, with the country specific coefficients intended to represent ownership of the different age classes not affecting steady state recruitment. This is no longer true in the competitive case, and these coefficients therefore determine the degree of overfishing caused by competition.

It is found that under the assumptions of the model Russia shifting their harvest towards mature fish and away from immature fish makes Norway better off. This happens because such a shift leads to Russia catching less fish in total, leaving Norway able to harvest more freely. It will be shown that the effect this has on the efficiency of the fishery depends on Norway's preferences. If Norway values harvest of mature fish higher than harvest of immature fish, the efficiency of the fishery will improve. If the opposite is true the efficiency will deteriorate, leading to lower

steady state stock levels. In the former case, Norwegian harvest of both mature and immature fish are rising in the Russian valuation of harvest of mature fish. This is an effect of increased stock values. Russian harvest of immature fish is falling while Russian harvest of mature fish is rising. Total harvest is falling because the mature stock is smaller than the immature stock, which is a consequence of the dynamics of the model.

After this, the thesis examines a situation where Russian valuation of harvest of mature fish increases at the expense of the Norwegian equivalent. This represents ownership of the mature age class shifting in Russias favour. The main result from this discussion is that the most socially efficient outcome is reached when the age classes are similarly distributed. This gives the best possible incentives as neither agent faces a situation where a disproportionate share of the costs of their harvests are born by the other. If the age classes are asymmetrically distributed, with one agent owning a large share of the immature age class and another owning a large share of the mature age class, both will be incentivized to overharvest as whatever escapement they leave will mainly benefit the other agent. More generally, you could say that if one age class is shared the other should be shared as well. This represents a sharp contrast to the case without differentiation between age classes, where competition is always bad. One important result found in this thesis is therefore that a partially shared fish stock can be the worst scenario of all.

The thesis therefore gives two main arguments why the climate change may not be as harmful for the Norwegian position as one might think. One is that Norway benefits from Russia shifting their harvest towards mature fish and the other is that a more even distribution of the mature age class leads to more efficient management of the fish stock.

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Chapter 1

Introduction

In economics competition is usually a good thing. Competitive markets generate efficient equilibria where price equals marginal cost. This gives rise to the first welfare theorem, which states that any competitive equilibrium is pareto efficient. This, of course, rests on a number of assumptions. One of these is that all goods are rival and excludable. This means that the good can only be consumed by one person, and whoever owns the good is able to prevent others from consuming it. There are, however, many goods for which this is not a very fitting description. A fish stock is an example of one such good. Fish stocks are certainly rival. If I eat a fish that means you are prevented from eating the same fish. They are, however, often not excludable. It can be very difficult, often impossible, to prevent others from harvesting a stock. This means that anyone harvesting will have an incentive to harvest more than what is socially optimal, as anything they leave behind may well be harvested by someone else. This causes the first welfare theorem to break down and the competitive equilibrium is no longer pareto efficient.

In the real world there are often restrictions to who is allowed to harvest a fish stock and to how much they are allowed to harvest. Quotas, taxes, gear restrictions and so on all help improve the situation and could in theory restore pareto efficiency. These measures all require some entity with authority over all the harvesting agents. Sometimes this entity exists, usually in the form of a national government. For this to be the case the fish stock must exclusively inhabit one nation's economic zone. If the fish stock is shared by two or more nations we are back to the inefficient competitive equilibrium. The difference is that the individual fishermen have been replaced by different countries all trying to maximize their piece of the cake.

This kind of competitive harvesting is the topic of this thesis. This is relevant for many of the world's fisheries. The Pacific salmon fishery, the Baltic cod fishery and the North-East Arctic cod fishery (which will from here on be referred to as the NEA cod fishery) are all examples of fisheries that are shared between different countries. This thesis will focus on the latter of these. The NEA cod fishery is for the most part shared between two countries: Norway and Russia. Other countries, most notably Iceland, also harvest the stock, but Norway and Russia are by far the most important agents. The two countries have signed an agreement determining how much each country's fishermen are allowed to harvest each year. For this reason one might think that the fishery is best described by cooperation between the two countries. This thesis will, however, for the most part analyze the situation as a competitive equilibrium.

One reason for this is that agreements to cooperate over common pool resources are by nature unstable (although less so when few different parties are involved). It is often possible for one or more of the agents taking part to be better off by unilateraly abandoning the agreement, or to cheat and harvest or pollute more than they are supposed to. Indeed, Hannesson (2011) finds that Russian enforcement of quotas and other restrictions are lacking and that this leads to overharvesting from the Russian side. Another reason is that the competitive equilibrium is the bargaining chip used by both countries in negotiating the agreement. A favourable competitive equilibrium means an agent's threats to abandon the agreement are much more credible, increasing their bargaining power. Understanding the competitive equilibrium is therefore important, even in a situation where the agents cooperate.

The aim of this thesis is to analyze the consequences of climate changes for the north-east Arctic cod fishery. Specifically, I will examine what would happen if a larger share of the mature stock was available in the Russian zone. Today, the mature cod spend most of their time out in the open ocean where they inhabit both the Norwegian and the Russian economic zones. In spawning season, however, they migrate towards the Norwegian coast. One possible effect of higher ocean temperatures is that new spawning areas are established further north and east, in Russian territory, as described by Stenevik and Sundby (2007). This would mean that the Russian share of the mature stock increases.

This scenario has also been analyzed in Hannesson (2006). This article finds that such a change improves the efficiency of the fishery as Nash equilibrium harvest rates are lowered and therefore closer to the optimum. Norway is actually better off as they weren't harvesting the spawning migration in the baseline case anyway. Hannesson's article also finds the counter intuitive result that if Russia gets a larger share of the total stock this could actually make Norway better off, as increased Russian conservation incentives and correspondingly reduced Norwegian conservation incentives leave Norway able harvest more freely. These results highlight the role of incentives and provide motivation for exploring these further.

While Hannesson uses a detailed, calibrated model, this thesis will use a simpler algebraic model. This implies a sacrifice of realism and the ability to predict magnitudes in order to get results that are easily interpretable. The goal is not to estimate catch volumes or efficient harvest patterns but rather to examine how the fundamental incentives work in such a situation. I will therefore use a model which isolates these incentives and shows how the strategic situation can be affected by the distribution of the stock. This thesis will discuss the actions and incentives of the agents in detail, while Hannesson's article is more focused on the results themselves.

One assumption that Hannesson makes is that the spawning migrations in the Russian and Norwegian zones are equally big, and his article does not discuss what would happen if this was not true, except in the case where ownership of the entire stock shifts in Russia's favour. In other words, he does not analyze the consequences of asymmetric distribution in much detail. The model used in this thesis is more flexible in that regard and will be used to show the outcome for all distributions ranging from full Norwegian ownsership to full Russian ownsership of the mature age class.

The model that I will use is an extended version of the one from Levhari and Mirman (1980). This framework was selected because it allows feedback solutions for the dynamic game. Modified versions of the Levhari-Mirman model have been used in several articles over the last decades. One example is Antoniadou et al. (2012) which adds uncertainty to the original model. It is then found that under the specific assumptions of the model, uncertainty doesn't affect harvesting patterns. For this reason, the model used in this thesis will not include uncertainty. Another example of interest for this thesis is Nieminen and Diekert (2014). This article explores the consequences of anticipated climate change. Recruitment and agent behaviour is similar to the original model, but climate change will cause the ownership of the stock to change after an uncertain amount of time. Both players know this change is coming, but not when. It is found that this regime change causes additional inefficiency as the agent that will lose ownership has less incentive to conserve the stock.

Blanchard and Pereau (2015) develop a model that is similar to the one used in this thesis. It is based on the Levhari and Mirman (1980) model and, like this thesis, it expands on the original model by having several stocks in stead of just one. The difference is that in my model the stocks represent different age classes, while in Blanchard and Pereau (2015) they represent different species. Their methods are therefore very similar to the ones that will be used in this paper but the application is different.

Another take on NEA cod fishery is found in Sumaila (1997). This article analyzes the fishery as a game between a coastal fleet and a trawler fleet rather than two countries. What separates the two fleets is their selectivity and the age classes targeted. The coastal fleet harvests only mature cod and this gives it an advantage in managing the stock. Under cooperation the trawler fleet is therefore bought out by the coastal fleet. This result can be reversed if the time horizon is short or if agents are impatient. Under competition the trawler fleet does better. Sumaila finds the Nash equilibrium for the competitive case and this is then used to find a bargaining solution for the cooperative game with side payments.

One lesson from Sumaila (1997) that is a common theme in many articles is the advantages of harvesting mature cod rather than immature cod. Too large harvests of immature cod leads to inefficiency as fish are not allowed to grow sufficiently to maximize the generated value from the fishery. This phenomenon is known as growth overfishing and is discussed in articles such as Quaas et al. (2013), Skonhoft et al. (2011), Diekert (2012) and Diekert et al. (2010). The latter of these articles discusses the Arctic cod fishery and finds that a large part of the inefficiency in the fishery is caused by agents not taking growth potential fully into account and therefore overharvesting the immature fish. This is a factor that could be important in the case of changed ownership of the mature age class as the conservation incentives would be altered.

The effect of climate change on international fishery agreements is discussed in Miller et al. (2013). The authors give several examples of how fishery agreements can collapse when the natural conditions are changed and explains how game theory can help understanding of these challenges. It is stressed that it is necessary to plan ahead for such events to avoid the losses and, in the worst case scenario, extinction of fish stocks that breakdown of agreements will lead to. This highlights the importance of analyses such as what this thesis aims to provide.

The thesis is organized as follows. The main part of this thesis will start with the introduction of the model at the beginning of chapter 2. The functions, variables and parameters are shown and explained. The model has two agents: Norway and Russia. These agents could have other names. They could, for example, be called USA and Canada if we were talking about the Pacific salmon fishery. The model is general enough that it could well be applied to other shared fish stock across the globe. For the purpose of this thesis, however, it is practical to call them Norway and Russia.

Then, in section 2.1, the cooperative solution is shown as a benchmark. This represents the ideal distribution and harvest patterns and will contrast with the competitive equilibrium that is the main focus of this thesis. I will set up the optimization problem and from there find optimal harvests as shares of the stock values. The next step is then to derive the steady state stock values and harvests. This is followed by a discussion of the results. Section 2.2 begins the analysis of the competitive case. The optimization problems of the individual agents are set up and conditions for optimal harvest subject to the actions of the other country are derived. These are then used to find equations characterising the Nash equilibrium.

Chapter 3 then continues the analysis by using these equations to examine the effects climate change could have on the steady state Nash equilibrium. This is done by graphical analysis. Effects on steady state stocks and harvest of immature and mature fish by both countries are shown for two scenarios, one where Russian valuation of harvest of mature fish increases in isolation (section 3.1) and one where it increases at the expense of Norwegian valuation of harvest of mature fish (section 3.2). I then discuss the mechanisms that lead to these results. The conclusion then provides further thoughts about the model and its results, as well as some discussion beyond the model.

All of the graphs and some of the more complicated calculations in this thesis have been generated using Matlab.

Chapter 2

The model

This model is designed to analyze competition between Norway and Russia over the NEA cod stock. The stock is modelled as consisting of two age groups: mature and immature cod. One period's escapement of immature fish becomes the next period's mature fish, while the escapement of mature fish spawns the next period's immature fish and then dies. The model setup is similar to the one in Levhari and Mirman (1980), except that there are two age classes. The dynamics are described by the following difference equations:

$$I_{t+1} = (M_t - H_{Mt})^{\alpha} \tag{2.1}$$

$$M_{t+1} = I_t - H_{It} \tag{2.2}$$

Here I denotes immature fish biomass while M denotes mature fish biomass. α is a parameter that determines how quickly the stock will regrow towards its equilibrium. The smaller α is, the faster this regrowth will be. It is assumed that $0 < \alpha < 1$, which implies that the recruitment function is concave so that an increase of the mature stock by a certain factor is going to increase the recruitment by a lower factor. If left unharvested, each age class will have an equilibrium biomass of 1. Immature escapement biomass will one for one turn into mature biomass the next period. This is because it is assumed that growth and mortality cancel each other out. This is of course a special case, but it is kept this way for mathematical simplicity. It is assumed that both age classes are available for harvest in both the Norwegian and the Russian zone but their distribution may be asymmetric. A share γ of the immature stock and a share δ of the mature stock is found in the Russian zone. It is assumed that δ is originally smaller than $\frac{1}{2}$. This is because the mature fish migrate to the Norwegian cost to spawn and hence are assumed to be available in greater quantities in the Norwegian zone. Both countries maximize the following utility function:

$$U^i = \sum_{t=0}^{\infty} \beta^t (p^i \ln H^i_{Mt} + q^i \ln H^i_{It}) \tag{2.3}$$

Utility is assumed to be logarithmic and separable. The latter assumption is made for mathematical tractability and may not be entirely realistic as one would expect the countries to care about total profit rather than attaching some intrinsic value to harvest of both age classes. β is a parameter that determines by how much future utility is discounted. A lower β implies that agents are more impatient. i denotes the nation which is either R for Russia or N for Norway. p^i and q^i are variables that determines how much utility the country gets from harvest of mature and immature fish respectively. They represent each country's profitability of harvesting the respective stock. It is assumed that greater density of fish leads to lower harvesting costs. Therefore an increase in the Russian share of the mature stock (δ) is going to lead to increased p^R.

2.1 Cooperative solution

I will start by showing the cooperative case as a benchmark. In this case the maximization problem is the following:

$$\max_{H^N_{Mt}, H^N_{It}, H^R_{Mt}, H^R_{It}} U = \sum_{t=0}^{\infty} \beta^t (p^N \ln H^N_{Mt} + q^N \ln H^N_{It} + p^R \ln H^R_{Mt} + q^R \ln H^R_{It}) \tag{2.4}$$

The cooperative solution is equal to the first best solution. This means that total utility is maximized. For this solution to be stable we must be in one of two cases. The first is that both are better off cooperating than competing. The second is that one is worse off, but side payments are possible so that the better off country compensates the worse off country. If side payments are not possible the worse off country will have no reason to stay with the cooperative solution, and it will collapse.

In order to solve this maximization problem I set up the Bellman equation:

$$\begin{aligned} &V(M_t, I_t) = \\ &\max_{H^N_{Mt}, H^N_{It}, H^R_{Mt}, H^R_{It}} \left(p^N \ln H^N_{Mt} + q^N \ln H^N_{It} + p^R \ln H^R_{Mt} + q^R \ln H^R_{It} + \beta V(M_{t+1}, I_{t+1})\right) \end{aligned} \tag{2.5}$$

This equation states that the value of the combined fish stock, which is the same as all discounted future utility, is equal to the sum of the utility from optimal harvest this period and the discounted value of the combined fish stock next period. Guessing that a functional form of $V = A \ln M + B \ln I + C$ solves the problem and inserting this into the Bellman equation gives

$$\begin{aligned} V(M_t, I_t) = \max_{H^N_{Mt}, H^N_{It}, H^R_{Mt}, H^R_{It}} & p^N \ln H^N_M + q^N \ln H^N_I + p^R \ln H^R_M + q^R \ln H^R_I \\ & + \beta \left(A \ln(I - H^N_I - H^R_I) + B \ln(M - H^N_M - H^R_M)^\alpha + C\right) \end{aligned} \tag{2.6}$$

The functional form used states that value is linear in the logarithm of both stocks. A and B serve as valuation coefficients for the mature and immature stock respectively. In order to find the solution of the problem I take the first order conditions with respect to the different harvests.

$$\frac{\partial V}{\partial H^N_M} = \frac{p^N}{H^N_M} - \frac{\alpha\beta B}{M - H^N_M - H^R_M} = 0 \tag{2.7}$$

$$\frac{\partial V}{\partial H_M^R} = \frac{p^R}{H_M^R} - \frac{\alpha\beta B}{M - H_M^N - H_M^R} = 0 \tag{2.8}$$

$$\frac{\partial V}{\partial H_I^N} = \frac{q^N}{H_I^N} - \frac{\beta A}{M - H_I^N - H_I^R} = 0 \tag{2.9}$$

$$\frac{\partial V}{\partial H_I^R} = \frac{q^R}{H_I^R} - \frac{\beta A}{M - H_I^N - H_I^R} = 0 \tag{2.10}$$

These conditions all say that the marginal utility from each country's harvest of each stock should equal the marginal social cost. The latter is the same as the discounted future utility foregone by removing fish and thus either preventing maturation or reproductive. Solving this equation system for the different harvests yields

$$H_M^N = \frac{p^N}{p^N + p^R + \alpha\beta B} M \tag{2.11}$$

$$H_M^R = \frac{p^R}{p^N + p^R + \alpha\beta B} M \tag{2.12}$$

$$H_I^N = \frac{q^N}{q^N + q^R + \beta A} I \tag{2.13}$$

$$H_I^R = \frac{q^R}{q^N + q^R + \beta A} I \tag{2.14}$$

Inserting these results into the Bellman equation gives

$$
\begin{aligned}
A \ln M + B \ln I + C = p^N \ln \frac{p^N}{p^N + p^R + \alpha\beta B} M + q^N \ln \frac{q^N}{q^N + q^R + \beta A} I \\
+ p^R \ln \frac{p^R}{p^N + p^R + \alpha\beta B} M + q^R \ln \frac{q^R}{q^N + q^R + \beta A} I \\
+ \beta \left(A \ln \frac{\beta A}{q^N + q^R + \beta A} I + \alpha B \ln \frac{\alpha\beta B}{p^N + p^R + \alpha\beta B} M + C \right)
\end{aligned} \tag{2.15}
$$

I then sort the terms.

$$
\begin{aligned}
A \ln M + B \ln I + C = (p^N + p^R + \alpha\beta B) \ln M + (q^N + q^R + \beta A) \ln I + p^N \ln \frac{p^N}{p^N + p^R + \alpha\beta B} \\
+ q^N \ln \frac{q^N}{q^N + q^R + \beta A} + p^R \ln \frac{p^R}{p^N + p^R + \alpha\beta B} + q^R \ln \frac{q^R}{q^N + q^R + \beta A} \\
+ \beta A \ln \frac{\beta A}{q^N + q^R + \beta A} + \alpha\beta B \ln \frac{\alpha\beta B}{p^N + p^R + \alpha\beta B} + \beta C
\end{aligned} \tag{2.16}
$$

Matching coefficients tells us $A = p^N + p^R + \alpha\beta B$ and $B = q^N + q^R + \beta A$. The rest of the right hand side is C. Notice that A and B are equal to the denominators in the optimal harvest functions (equations 2.11 through 2.14). This tells us that each country harvests a share of each stock equal to their valuation of harvest relative to the total valuation of the stock.

Solving for A and B gives the following values:

$$
A = \frac{p^N + p^R + \alpha\beta(q^N + q^R)}{1 - \alpha\beta^2} \tag{2.17}
$$

$$
B = \frac{q^N + q^R + \beta(p^N + p^R)}{1 - \alpha\beta^2} \tag{2.18}
$$

The stock valuation coefficients are linearly increasing in all of the harvest coefficients. Insertion into the harvest functions gives

$$H_M^N = \frac{p^N(1-\alpha\beta^2)}{p^N + p^R + \alpha\beta(q^N + q^R)} M \tag{2.19}$$

$$H_M^R = \frac{p^R(1-\alpha\beta^2)}{p^N + p^R + \alpha\beta(q^N + q^R)} M \tag{2.20}$$

$$H_I^N = \frac{q^N(1-\alpha\beta^2)}{q^N + q^R + \beta(p^N + p^R)} I \tag{2.21}$$

$$H_I^R = \frac{q^R(1-\alpha\beta^2)}{q^N + q^R + \beta(p^N + p^R)} I \tag{2.22}$$

To find the steady state solution we define M and I as equal to M^{SS} and I^{SS} (steady state stock levels of mature and immature fish) and insert them into equations 2.1 and 2.2. This results in the following equation system:

$$M^{SS} = I^{SS} - H_I^N(I^{SS}) - H_I^R(I^{SS}) \tag{2.23}$$

$$I^{SS} = \left(M^{SS} - H_M^N(M^{SS}) - H_M^R(M^{SS})\right)^{\alpha} \tag{2.24}$$

To find the steady state stocks we then insert the equations for optimal harvest and solve for M^{SS} and I^{SS}.

$$I^{SS} = (\alpha\beta^2)^{\frac{\alpha}{1-\alpha}} \tag{2.25}$$

$$M^{SS} = \beta \frac{(p^N + p^R) + \alpha\beta(q^N + q^R)}{q^N + q^R + \beta(p^N + p^R)} (\alpha\beta^2)^{\frac{\alpha}{1-\alpha}} \tag{2.26}$$

Both stocks are increasing in β. This is unsurprising as caring more about the future will intuitively lead to less fish being harvested, which will lead to higher recruitment. The effect of α is ambiguous. A higher α leads to lower recruitment for any given escapement of mature fish, but also to lower harvest as a share of the stock for both age classes. It does, however seem reasonable to expect the direct effect to dominate. In order to find the total effect of α on I^{SS} we take the derivative of equation 2.25 with respect to α. This yields the following:

$$\frac{\partial I^{SS}}{\partial \alpha} = \left(\log(\alpha\beta^2) - alpha + 1\right) \frac{(\alpha\beta^2)^{\frac{\alpha}{1-\alpha}}}{(\alpha - 1)^2} \tag{2.27}$$

$(\alpha - 1)^2$ is a square and therefore always positive. So is $(\alpha\beta^2)^{\frac{\alpha}{1-\alpha}}$. The sign of the derivative is therefore determined by the sign of the expression $\log(\alpha\beta^2) - alpha + 1$. this is negative as long as the following equation holds:

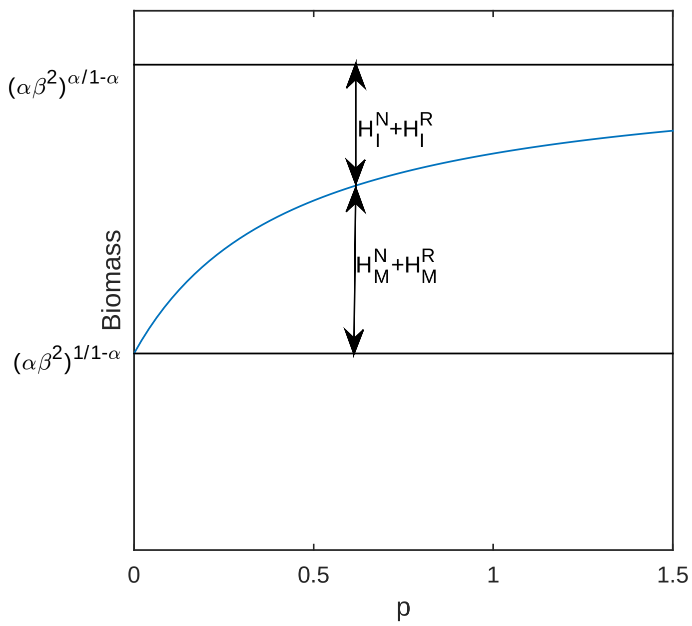
$$\alpha - \log \alpha > 1 + 2 \log \beta \tag{2.28}$$

This is true for any α between 0 and 1 as long as β is between 0 and 1. If this is the case the right hand side will always be less than 1, while the left hand side will tend to one from above, but not actually reach 1 before $\alpha = 1$ (because $\log 1 = 0$). Therefore, equation 2.28 always holds within the assumptions of the model.

It is interesting to see that the steady state stock of immature fish is independent of p^N, p^R, q^N and q^R. In fact, it is almost identical to the steady state level found in Levhari and Mirman (1980). In that paper the steady state level of the stock is equal to $(\alpha\beta)^{\frac{\alpha}{1-\alpha}}$. The only difference is that here β is replaced by β^2. The reason for this is that in Levhari and Mirman fish will be able to reproduce right away, while in this model any fish spawned will be unable to reproduce for one more period. This means their value is discounted for two periods rather than just one.

One implication of these steady state equations is that the escapement of mature

Figure 2.1: Harvest in the cooperative case



fish in all periods has to equal $(\alpha\beta^2)^{\frac{1}{1-\alpha}}$, as this is the escapement that gives the optimal recruitment. Again, this is independent of utility coefficients. This means that the total biomass in the ocean and the total biomass harvested is the same regardless of any of the model's nation specific variables. The impact of p^N, p^R, q^N and q^R on the steady state solution is to determine how much of the harvested biomass is mature fish and immature fish, and how it is distributed between the countries. This is illustrated in Figure 2.1. This figure shows what happens as p^R and p^N, in this case assumed to be equal, increase. The horizontal line at the top of the screen shows the recruitment, or the stock of immature fish, while the lower horizontal line shows escapement of mature fish. The curve in between shows total harvest of mature fish. For any p, the distance between the curve and the lower line is equal to total harvest of mature fish, while the distance between the curve and the top line is equal to total harvest of immature fish.

To find expressions for steady state harvest I insert the steady state stocks into the optimal harvest functions.

$$H_M^N = \frac{\beta p^N(1-\alpha\beta^2)}{q^N + q^R + \beta(p^N + p^R)}(\alpha\beta^2)^{\frac{\alpha}{1-\alpha}} \tag{2.29}$$

$$H_M^R = \frac{\beta p^R(1-\alpha\beta^2)}{q^N + q^R + \beta(p^N + p^R)}(\alpha\beta^2)^{\frac{\alpha}{1-\alpha}} \tag{2.30}$$

$$H_I^N = \frac{q^N(1-\alpha\beta^2)}{q^N + q^R + \beta(p^N + p^R)}(\alpha\beta^2)^{\frac{\alpha}{1-\alpha}} \tag{2.31}$$

$$H_I^R = \frac{q^R(1-\alpha\beta^2)}{q^N + q^R + \beta(p^N + p^R)}(\alpha\beta^2)^{\frac{\alpha}{1-\alpha}} \tag{2.32}$$

This gives a very simple and intuitive harvest pattern. Each harvest is proportional to the country's valuation of harvest for the age class in question relative to the sum of all the valuations of harvest. In total a share of $(1-\alpha\beta^2)$ of the recruitment is harvested each period, giving a survival rate of $\alpha\beta^2$, exactly what is needed to spawn $(\alpha\beta^2)^{\frac{\alpha}{1-\alpha}}$ new fish. To see this, multiply $\alpha\beta^2$ with $(\alpha\beta^2)^{\frac{\alpha}{1-\alpha}}$. This will give $(\alpha\beta^2)^{\frac{1}{1-\alpha}}$, the required escapement of mature fish.

Notice that each country's harvest of mature fish contains the factor β while the harvests of immature fish do not. This is because for each generation a certain amount will be harvested, and harvesting the generation at its immature stage gives utility earlier. Therefore harvest of mature fish is discounted, so that impatient agents will harvest more immature fish.

One result from this model that is not always found is that both age classess are harvested, even in the cooperative case. It is often the case that some age classes are left unharvested because it is more profitable to let them grow. An example of this is found in Skonhoft and Gong (2014), where the age class with the highest ratio of price to fertility is completely harvested before any other age class is touched. Hannesson (2006) similarly finds that the harvest in the north-east Arctic cod fishery is maximized if only mature fish are harvested. The reason why this is not the case in this model is the separability and concavity of the utility function. The fact that harvest of one age class does not affect the marginal utility of harvesting the other age class ensures that it will, assuming the coefficients are positive, be optimal to harvest both mature and immature fish.

2.2 Competitive equilibrium

Now that the first best allocation has been established I move on to the competitive case. The difference is that now each country maximizes its own utility subject to the other country's harvest, as opposed to some benevolent social planner maximizing total utility. Under otherwise the same assumptions as before each country's Bellman equation is the following:

$$V(M_t, I_t) = \max_{H^i_{Mt}, H^i_{It}} p^i \ln H^i_{Mt} + q^i \ln H^i_{It} + \beta V(M_{t+1}, I_{t+1}) \tag{2.33}$$

Inserting the recruitment functions and using the same guess for functional form as before this becomes

$$V(M, I) = \max_{H^i_{Mt}, H^i_{It}} p^i \ln H^i_M + q^i \ln H^i_I + \beta(A^i \ln(I - H^i_I - H^j_I) + B^i \ln(M - H^i_M - H^j_M)^\alpha + C^i) \tag{2.34}$$

Here i denotes either Norway or Russia and j denotes the other country. Taking the first order conditions yields the following best reply functions:

$$H^i_M = \frac{p^i(M - H^j_M)}{p^i + \alpha\beta B^i} \tag{2.35}$$

$$H^i_I = \frac{q^i(I - H^j_I)}{q^i + \beta A^i} \tag{2.36}$$

Inserting the corresponding best reply functions of the other player gives the following equations describing the Nash equilibrium:

$$H^i_M = \frac{p^i}{p^i + p^j \frac{B^i}{B^j} + \alpha\beta B^i} M \tag{2.37}$$

$$H^i_I = \frac{q^i}{q^i + q^j \frac{A^i}{A^j} + \beta A^i} I \tag{2.38}$$

These equations look relatively similar to the corresponding equations in the cooperative case. There are however two key differences that will be discussed below.

Inserting the above equations into the Bellman equation gives the following expressions for A and B:

$$A^i = \frac{p^i + \alpha\beta q^i}{1 - \alpha\beta^2} \tag{2.39}$$

$$B^i = \frac{q^i + \beta p^i}{1 - \alpha\beta^2} \tag{2.40}$$

This by itself tells us that competition leads to inefficiency. A and B determine the value that each country attaches to the stock (or at least the logarithm of it), and it is easy to see that they are lower in the competitive case than in the cooperative case. Here they only include the country's own valuation of harvest, while in the cooperative case both countries' valuations were included. This implies that neither country takes into account how their harvests affect the other, leading to inefficiently high harvests.

Notice that if $A^i = A^j$ and $B^i = B^j$ the harvest equations (2.37 and 2.38) are of the same form as the corresponding equations in the cooperative case (equations 2.11 through 2.14). The equilibrium would still be inefficient, however, as the As and Bs are different from the cooperative case. This would be a special case however. In the case where they are not equal the harvest fractions are further skewed compared to the first-best case. It has already been established that the harvest shares will be too high. This is because part of the costs are not internalized. The second mechanism has a similar explanation but a slightly different impact. If one country has a higher valuation of one stock, this will cause it to harvest less of the opposite stock as its marginal cost of harvest (in terms of future recruitment) has increased. This will, however cause the other country to harvest more as lower harvest from one country causes lower marginal costs for the other. This did not happen in the cooperative case as both countries internalized all costs.

Inserting the As and Bs into the above equations gives the following harvest shares:

$$H_I^i = \frac{q^i(p^j + \alpha\beta q^j)(1-\alpha\beta^2)}{q^j p^i + p^j q^i + \alpha\beta(2-\alpha\beta^2)q^j q^i + \beta p^j p^i} I \tag{2.41}$$

$$H_M^i = \frac{p^i(q^j + \beta p^j)(1-\alpha\beta^2)}{q^j p^i + p^j q^i + \beta(2-\alpha\beta^2)p^j p^i + \alpha\beta q^j q^i} M \tag{2.42}$$

Using the same method as in the cooperative case I find the following values for steady state stocks:

$$M^{SS} = \left(\alpha\beta^2 \frac{\eta}{\theta}\right)^{\frac{\alpha}{1-\alpha}} \beta \left(\frac{\epsilon}{\kappa}\right)^{\frac{1}{1-\alpha}} \tag{2.43}$$

$$I^{SS} = \left(\alpha\beta^2 \frac{\eta\epsilon}{\theta\kappa}\right)^{\frac{\alpha}{1-\alpha}} \tag{2.44}$$

η, ϵ, θ and κ are all auxiliary parameters and are defined as follows:

$$\eta = q^N q^R + \beta(p^N q^R + p^R q^N + \beta p^N p^R) \tag{2.45}$$

$$\epsilon = p^N p^R + \alpha\beta(q^N p^R + q^R p^N + \alpha\beta q^N q^R) \tag{2.46}$$

$$\theta = q^R p^N + q^N p^R + \beta(2-\alpha\beta^2) p^N p^R + \alpha\beta q^N q^R \tag{2.47}$$

$$\kappa = q^R p^N + q^N p^R + \alpha\beta(2-\alpha\beta^2) q^N q^R + \beta p^N p^R \tag{2.48}$$

Inserting steady state stock levels into the optimal harvest functions yields

$$H_I^i = q^i(p^j + \alpha\beta q^j)(1-\alpha\beta^2)\left(\alpha\beta^2 \frac{\eta\epsilon}{\theta}\right)^{\frac{\alpha}{1-\alpha}} \kappa^{-\frac{1}{1-\alpha}} \tag{2.49}$$

$$H_M^i = p^i(q^j + \beta p^j)(1-\alpha\beta^2)\left(\alpha\beta^2\eta\right)^{\frac{\alpha}{1-\alpha}} \left(\frac{\epsilon}{\kappa\theta}\right)^{\frac{1}{1-\alpha}} \tag{2.50}$$

Chapter 3

Comparative statics

3.1 The effect of p^R

I will now turn to comparative statics. Using the steady state harvests and stock levels derived earlier I will explore what happens to the steady state solution as key variables change. First, I will examine the case where p^R increases while everything else is kept constant. This is an interesting case because it reveals how one country's (Russia's in this case) harvesting behaviour affects both the efficiency of stock management and the other country's situation (Norway in this case). I will later, in section 3.2, study the case where p^N, p^R, q^N and q^R are defined as functions of the country's share of the relevant stock.

Due to the difficulties of interpreting mathematical results when the equations have reached the level of complexity seen above, I will in this section primarily use graphical analysis. To do this certain assumptions have to be made about the numerical values of the parameters. Unless stated otherwise, these are the assumed numerical values used in the graphs of this chapter: $\alpha = 0.5, \beta = 0.9, q^R = q^N = 0.4$ and $p^N = 0.8$. Some of the results will rely on p^N exceeding q^N. These are discussed in more detail at the end of the section.

Figure 3.1 illustrates how the steady state stocks of immature and mature fish evolve as p^R increases while all other variables are kept constant. It is clear from the diagrams that increased Russian valuation of harvest of mature fish is beneficial for stock levels. Both stocks are rising in p^R, particularly for low values. $p^R = 0$ gives very low stock levels. Another observation that can be made from these graphs is

Figure 3.1: Steady state stocks as p^R increases

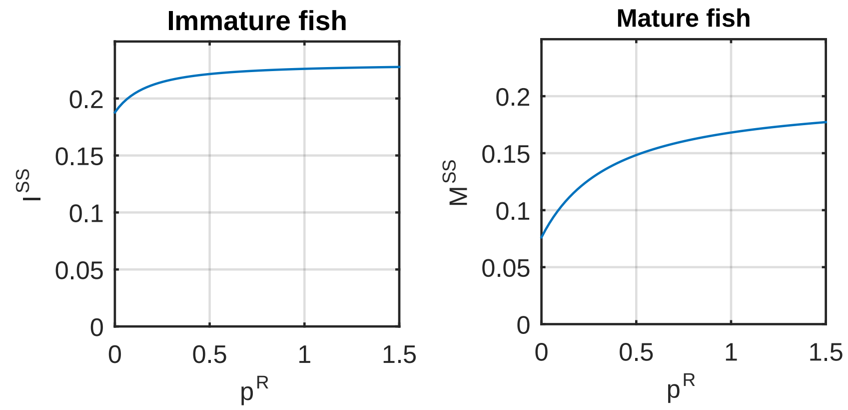
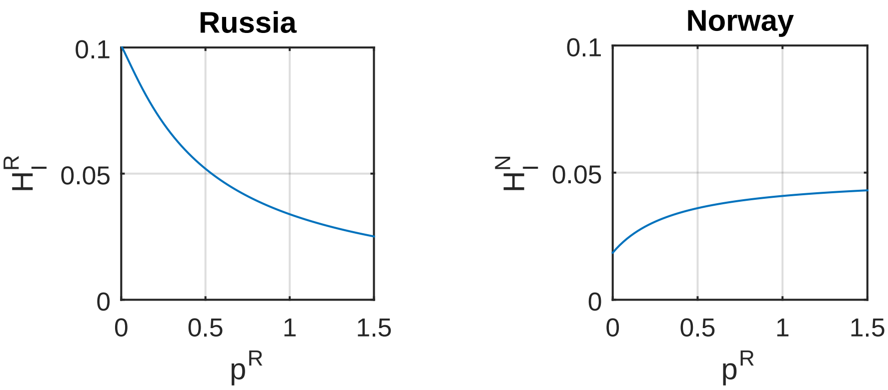


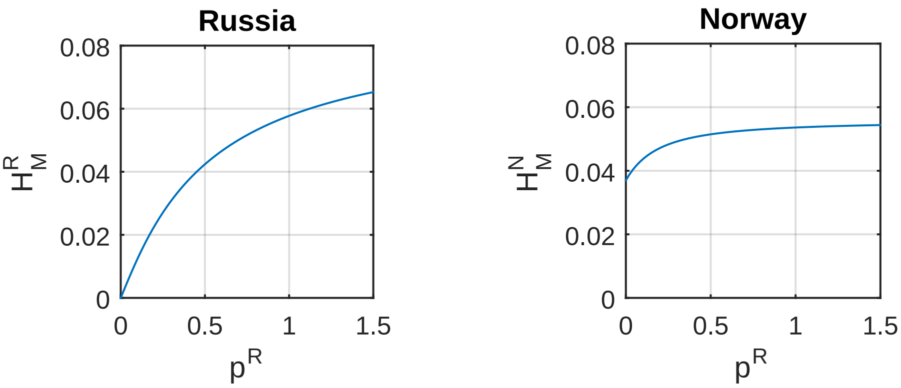
Figure 3.2: Harvest of immature fish



that the impact of p^R is much stronger on the mature stock than on the immature stock. To explain these findings we look at what happens to steady state harvests.

The first graph of Figure 3.2 plots Russian harvest of immature fish against p^R. This graph captures the most important impact of the Russian valuation of harvest of mature fish. There are large variations, with harvests at $p^R = 0$ being about 4 times the harvests at high values of p^R. When Russian fishermen are unable to profitably harvest mature fish, their incentives to let immature fish grow are greatly diminished. The only thing preventing them from harvesting the entire stock of immature fish is the fact that they need to let some of them grow up in order for new immature fish to be spawned. As p^R increases, so does their incentive

Figure 3.3: Harvest of mature fish

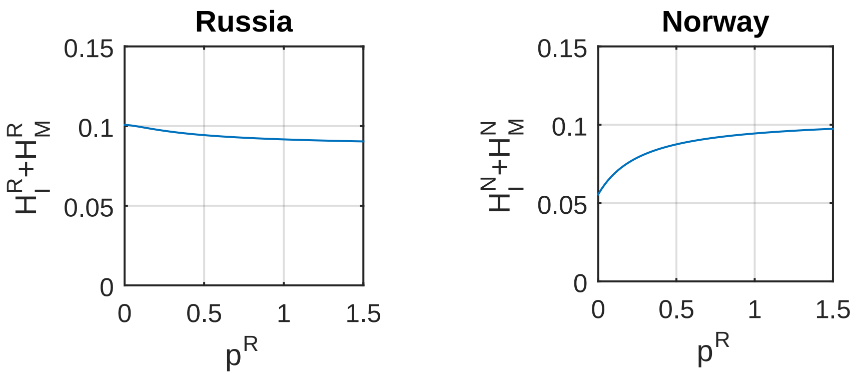


to conserve the immature stock and steady state harvest of immature fish decreases steeply. This is a big part of the explanation for the large variation in the mature stock. When p^R is low, Russian harvest of immature fish is high which leads to few fish ever reaching maturity. The impact on the stock of immature fish is much smaller, in part because of the concavity of the recruitment function, which implies that a decrease in the escapement of mature fish will give a smaller decrease in recruitment, and in part because of how harvests of mature fish are affected. This will be discussed further.

The second graph of Figure 3.2 plots Norwegian harvests of immature fish against p^R. The effect is, unsurprisingly, opposite of the effect on the Russian harvest. When Russia harvests a large number of immature fish this leads Norway, who still harvests mature fish, to harvest few immature fish in order to conserve the stock and increase recruitment. For low p^R and hence high Russian harvest of immature fish, Norwegian harvest of the same stock is low, while for sufficiently high p^R Norwegian harvest of immature fish exceeds Russian harvest. This gives a moderating effect on the steady state stock levels.

The first graph of Figure 3.3 shows the effect on Russian harvest of mature fish. This curve starts at the origin as there will be no harvest when there is no profitability. It then rises as p^R increases. This is another part of the explanation for why the effect on the mature stock is so much stronger than the effect on the immature stock. When p^R is low, Russian harvest of immature fish is high while Russian harvest of mature fish is low. For high values of p^R it is the opposite.

Figure 3.4: Total harvest



This implies that the escapement of mature fish will vary less than the stock of mature fish. In cases where the steady state stock of mature fish is large harvests will be large, while in cases where the steady state stock is small harvests will also be small. Hence the escapement of mature fish will not be as sensitive to p^R as the stock levels, and therefore neither will the stock of immature fish.

The second graph of figure 3.3 illustrates what happens to Norwegian harvest of mature fish as p^R increases. While the curve is rising for all values of p^R, it is easy to see that the effect is much smaller than on the other harvests, especially the Russian ones. The explanation for this lies in the Russian behaviour. Russian harvest of mature fish moves in a pattern that is very similar to the changes in the stock of mature fish. From the Norwegian point of view there are therefore two effects that to a large degree cancel each other out. A large stock of mature fish is accompanied by a large Russian harvest, while a small stock is accompanied by a small Russian harvest. In sum this implies a relatively weak effect on Norwegian harvest.

It is interesting to see that Norwegian harvests of both age classes are increasing in p^R. In other words, an isolated increase in Russian profitability of harvesting mature fish makes Norway strictly better off. This happens because an increase in p^R not only shifts Russian harvest towards mature fish, it also causes Rusia to harvest less biomass in total. This is illustarted in Figure 3.4. To understand this result we must go back to equations 2.41 and 2.42, which shows the agents' harvest

Figure 3.5: Norwegian harvest of mature fish under alternative assumptions

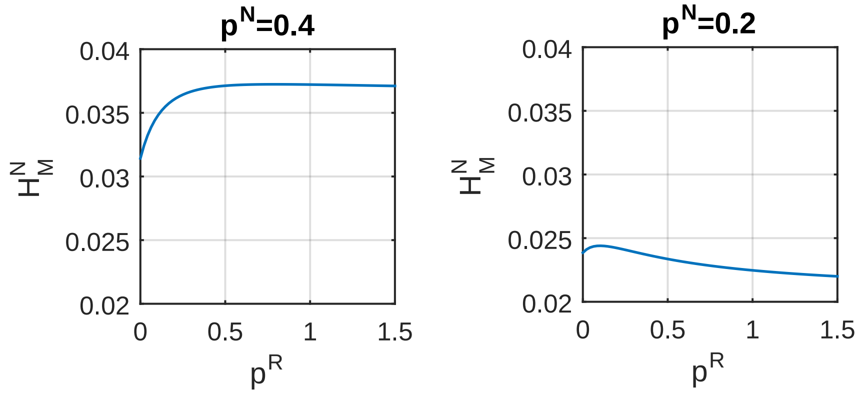
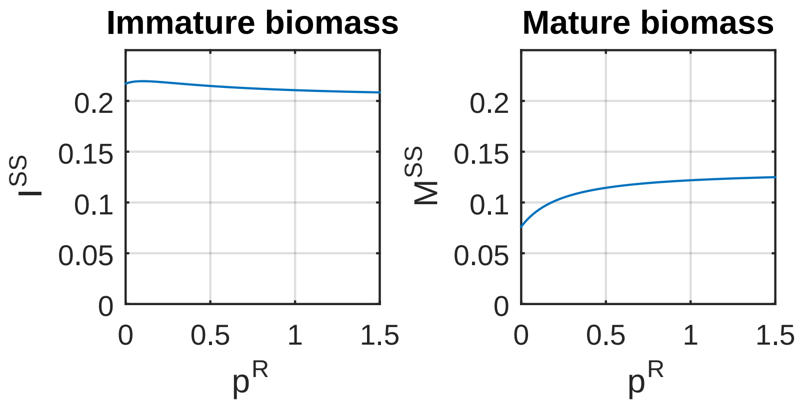


Figure 3.6: Steady state biomass levels when $p^N = 0.2$



of each age class as a share of the stock. It is clear that an increase in p^R will lead to Russia harvesting a lower share of the immature stock and a higher share of the mature stock. In this model, the mature stock is always smaller than the immature stock if agents are harvesting. This therefore leads to Russia's total catch decreasing. Norway's total catch, on the other hand, is increasing. This happens for two reasons. One is that the size of both stocks are increasing. The other is that Norway shift their harvest towards the larger immature stock.

While Norway is indeed made better off by increasing p^R, the result that Norwegian harvest of mature fish is increasing is dependent on the numerical values of the parameters as illustarted in Figure 3.5. Specifically, p^N has to exceed q^N. In words Norway must value harvest of mature fish higher than harvest of immature fish. If this is not the case Norway may instead decide to harvest less of the mature fish as a reaction to the increased Russian harvest of this age group. In Figure 3.3 it is assumed that p^N is twice as high as q^N. This turns out to be sufficient for the effect of a larger stock to dominate the effect of a desire for more immature fish. If on the other hand $p^N = q^N = 0.4$, the desire for higher recruitment eventually causes Norwegian harvest of mature fish to fall as p^R increases. In the case that $p^N = 0.2$, half of q^N, this happens earlier.

Another result that is changed when $p^N = 0.2$ is the one illustrated in figure 3.1, that steady state recruitment, and therefore I^{SS}, is increasing in p^R. As illustrated by figure 3.6, immature biomass is actually falling in p^R after a certain point. This is caused by Norway preferring to harvest immature fish and Russia preferring to harvest mature fish. This leads to a situation where what either country does not harvest of their preferred age class will mainly benefit the other country, leaving both sides with powerful incentives for overharvesting. The steady state stock of mature fish is rising in p^R, however. This is because Russia will be harvesting less immature fish and more mature fish, leading to a larger mature age class but a lower mature escapement.

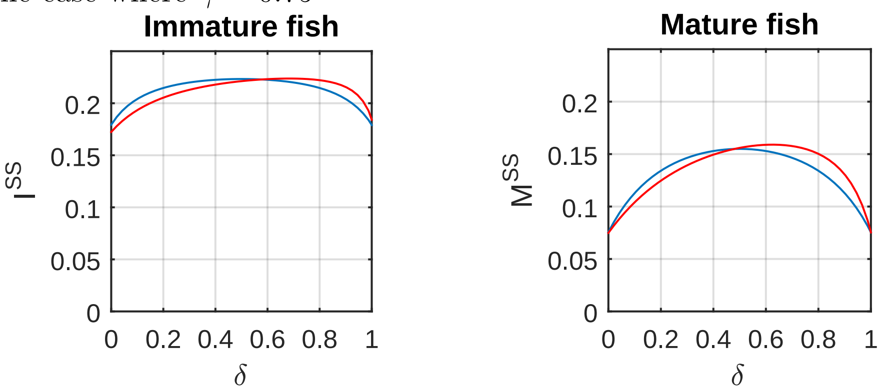
3.2 Effects of the ownership of the age classes

The above analysis describes the case where Russian profitability of harvest increases while everything else is kept constant. In a situation where the stock changes spawning areas and migration patterns this might not be the most realistic description. I will therefore now analyze the case where the harvest valuation coefficients are dependent on the share of the stock. The new coefficients are defined as follows:

$$p^R = \delta p \tag{3.1}$$

$$p^N = (1 - \delta)p \tag{3.2}$$

Figure 3.7: Steady state stocks. Blue curve is for the case where $\gamma = 0.5$, red curve is for the case where $\gamma = 0.75$



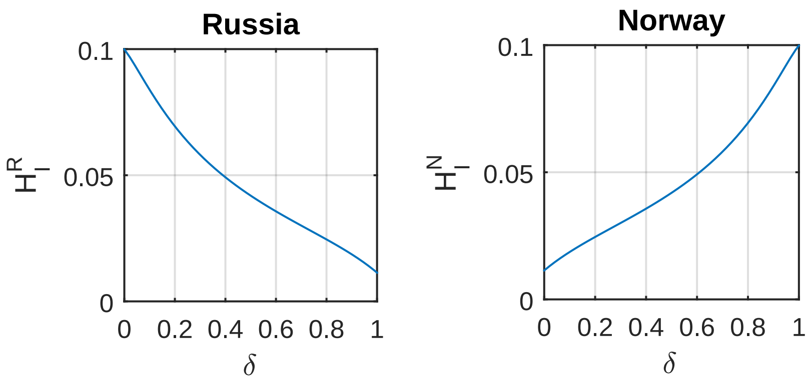
$$q^R = \gamma q \tag{3.3}$$

$$q^N = (1 - \gamma)q \tag{3.4}$$

Here δ is the Russian share of the mature stock and γ is the Russian share of the immature stock. p and q is the valuation a country would have if it owned all of the stock of mature and immature fish respectively. They are assumed equal to 1.4 and 0.8 respectively. It is assumed that this valuation is split between the countries with shares equal to the shares of the stock. This very simple functional form was selected because it has some key properties. It ensures that valuation of harvest is increasing in the country's share of the stock and that a share equal to zero gives zero valuation of harvest, ensuring that there is no harvest of the stock in question. I will assume that $\gamma = 0.5$. The following analysis therefore shows the impact of the distribution of mature fish assuming that the stock of immature fish is evenly distributed.

The first graph of Figure 3.7 shows what happens to the steady state stock of immature fish as δ increases from zero to one. The blue curve represents the case where the immature age class is evenly shared, $\gamma = 0.5$. This curve has a top at

Figure 3.8: Harvests of immature fish

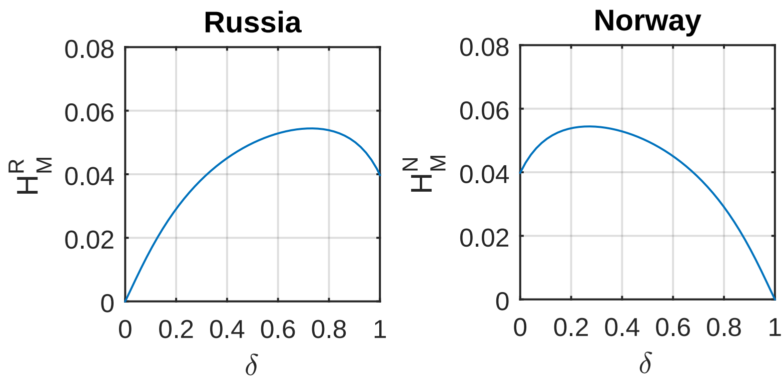


$\delta = 0.5$. In other words, under the assumption that the immature stock is split evenly between the countries it is optimal for the mature stock to be split evenly as well. If one country has a larger share of the immature stock than the other, it is socially optimal for that country to have a larger share of the mature stock as well. This is illustrated by the red curve, which shows the effect of δ when $\gamma = 0.75$. The entire curve shift to the right, indicating that the most efficient outcome is reached when the mature stock is shared unevenly as well. In this context, optimal means the division of the mature stock that gives the most efficient harvest levels. This is still not efficient in the first best sense, but it is the distribution that minimizes the inefficiency caused by competitive harvesting. The second graph of Figure 3.7 shows the development of the mature stock as delta increases and it tells a similar story, supporting the above result. Again, the impact is stronger on the mature stock than on the immature stock. As before, one important reason is the concavity of the recruitment function.

The graphs of Figure 3.7 are symmetric. This is a consequence of the assumption that $\gamma = 0.5$. This assumption is also going to lead to symmetry in the other figures of this section, in the sense that the graphs showing harvest for Norway and Russia are going to be mirror images of each other. As long as the stock of immature fish is evenly shared, Norway at, for example, $\delta = 0.4$ is going to behave identically to Russia at $\delta = 0.6$

Figure 3.8 plots Russian and Norwegian harvests of immature fish against δ. The graphs show that harvests of immature fish are falling as a country's share of

Figure 3.9: Harvests of mature fish



the mature stock rises. This is because, similarly to what happened to Russia in the previous section, higher profitability of harvesting mature fish makes the country desire more fish of this age class, and therefore they harvest fewer immature fish. The opposite is true for the other country as their reduced profitability of harvesting mature fish shift their harvests in the direction of immature fish. These effects then amplify each other. For example, if δ increases, Russia will reduce their harvest of immature fish, while Norwegian harvests will increase. These are both direct effects of the change in δ. Then Norway will realize that Russia has reduced their harvest of immature fish causing them to further increase their own, while Russia realizes that Norwegian harvests have increased, causing them to further reduce their own harvests.

Figure 3.9 plots harvests of mature fish against δ. It is interesting to see that these curves have internal maxima. This means that if a country's share of the mature stock is sufficiently high, a reduced share would would lead to increased harvest of mature fish. This happens because a low share of the mature stock for the other country leads to low conservation incentives and therefore a large harvest of immature fish. This then leads to low stock levels, particularly of mature fish. Norwegian harvest of mature fish relative to the stock is always decreasing in δ, but as the stock is also increasing up to $\delta = 0.5$ the effect on absolute harvest is ambiguous.

So, then, how does Norwegian utility depend on δ? As it happens, it is always increasing. This is not a result with a lot of economic insight, but rather a mathematical peculiarity of the modeling setup. Harvests are always between zero and one and hence the logarithms of harvest are always negative. Therefore an increase in δ, which makes Norway care less about harvest of mature fish, will always increase Norwegian utility by reducing the negative impact from the logarithm of harvest. Hence Norwegian utility is in this case not a very interesting variable. It is however clear from the above figures that it is not in either country's interest to have all of the mature stock. This gives the minimum harvest of immature fish and a harvest of mature fish that is lower than the maximum.

This is an interesting result. It shows that if one country has exclusive access to the mature stock while the immature stock is evenly divided they are actually better off if they allow limited access to the other country. Something similar does, of course, occur in reality as Norway allows Russia access to the spawning migration. The findings of this thesis suggests that is a wise thing to do. In this model, a country with little access to the mature stock will harvest the immature stock with very little thought for conservation, because they know that much of the escapement will be harvested when they reach maturity by the other country while they themselves are left out. This gives a massive incentive for growth overfishing. One could say they are holding the immature stock hostage, but in this situation there is no communication or agreements between the different parts. Each country is merely doing the best they can subject to the actions of the other country. If side payments were possible the country without access to the mature stock would be able to extract a significant ransom in exchange for not overharvesting the immature stock.

Chapter 4

Conclusion and discussion

The competitive harvest analysis has yielded two particularly interesting results. The first is the result that if one country shifts its harvest towards mature fish this leads to increased steady state stocks and the other country being better off. As was explained in section 3.1, this has the simple explanation that the mature stock is smaller, so that increasing harvest of mature fish at the expense of harvest of immature fish leads to fewer fish being caught in total. We learn from the analysis of the cooperative case (section 2.1) that the total harvest is important in this model. There, it was found that the total catch was unchanged by the ps and qs. In the competitive case, however, this is no longer true and the degree of overfishing (deviation from the first best solution) is dependent on these parameters. As has been shown, an increase in one country's valuation of harvest of mature fish leads the steady state biomass of both age classes to increase, bringing the Nash equilibrium closer to the first best scenario.

This result relies on the assumption that $p^N > q^N$. If this is not the case, an increase in p^R could lead to decreased steady state biomass as Russia will be harvesting the mature stock heavily while Norway will be harvesting the immature stock heavily. Therefore neither agent has much incentive to conserve as what they don't harvest will benefit the other agent. This leads to steady state biomass dropping. This situation is illustrated in figure 3.6.

This brings us to the second result, namely that if one age class is shared then the other should be shared as well. This is closely related to the discussion above. The reason why it was found that an increase in p^R led to increased steady state biomass is that it caused both countries to conserve the immature fish. If only one age class is shared while the other is fully owned by one country, neither age class will be spared as each country will heavily harvest opposite age classes. Keeping the distribution of the two stocks similar therefore provides the best possible conservation incentives. Asymmetric distribution inevitably leads to a situation where the majority of the costs of overfishing is born by the other country.

It would have been interesting to see what happens if both γ and δ were to change together. This would represent the case where ownership of the entire stock was changed rather than just ownership of the mature stock. Unfortunately this framework is not suited to analyze this situation. If γ and δ is replaced by a common variable in this model, this variable would not affect optimization. Mathematically, the proximate reason for this is that inserting equations 3.1 through 3.4 into the steady state equations with $\gamma = \delta$ results in all the γs and δs canceling out. Additionally, if $\gamma = \delta = 0$ or $\gamma = \delta = 1$, I have divided by zero several places. A more fundamental explanation is that it is only the values of the valuation coefficients relative to each other that matter in this model. For example, a decrease of both p^N and q^N by the same factor does not affect the optimization of Norway and therefore not of Russia. Such a change would still leave Norway with the same cost-benefit analysis over how much to harvest of each stock. Although the gain of harvesting has decreased, the cost has also decreased by the same factor as the country now has a lower valuation of the other stock.

A decrease in a country's p and q represents a decrease in profitability and therefore lower utility from harvest. However, as long as the coefficient is greater than 0 harvest will never be unprofitable. There are also no increasing marginal costs. Therefore, a low share of both stocks would not prevent large harvests. Utility would certainly be lower but only because less profit is made for each unit harvested. Harvests would be just as great as before.

Although the model developed in this thesis is unsuited to analyze the situation it is generally the case that competition leads to inefficiency in fisheries. A sole owner will take all effects into consideration and it will not overharvest as all costs would be born by him. With competition this is no longer the case as part of the costs will be born by someone else. Indeed, in this model a sole owner would achieve the first best exploitation of the stock. The literature is practically unanimous about competition leading to inefficiency. One emprirical example of this is Diekert et al. (2010), which finds that the inefficiency in the arctic cod fishery is caused by the strategic situation. It therefore seems to be clear that competitive harvesting is detrimental to efficiency. This makes the findings from Figure 3.7 all the more interesting. This model yields the result that if one age class is shared between two countries then the most efficient outcome is reached if the other age class is shared as well. In other words, sharing the other age class actually leads to improved efficiency.

This is a result that highlights some important aspects of competitive harvesting. While competition is generally bad, the lack of it can under certain circumstances be equally destructive. This model gives an example of how partial competition can be the worst scenario of all. This happens because the inability to harvest one of the age classes leaves the country in question with little incentive for conservation as any fish they leave in the water will mainly benefit someone else. This leads the country in question to drastically overharvest the age class they do have access to.

In the extreme case that one of γ and δ is equal to 0 and the other is equal to 1 the situation turns into a sequential fishery similar to that examined in Laukkanen (2003) and Laukkanen (2005). One country will have exclusive access to the immature stock and another will have exclusive access to the mature stock. In this case what one country doesn't harvest of its respective stock will only benefit the other country next period, which means neither country will have much incentive for conservation. This is of course not a very likely scenario for cod, as it would require the mature and immature stock to exclusively inhabit different economic zones with no overlap in their inhabited areas.

It should be mentioned that the severity of the problems caused by assymmetric distribution of the age classes are probably overstated in this model. One reason for this is that, as already mentioned, there are no barriers to how much fish can be harvested. In the numerical example given in figures 3.7 through 3.9 a country with no access to the mature stock will actually harvest more than their share of immature fish. This would of course be impossible in a situation where the countries close their economic zones to each other, and increasing costs of harvest would likely make it impossible to harvest all the fish in the country's own zone. The incentives explored here would still apply, however.

On the face of it, climate change leading to cod shifting their spawning grounds from Norwegian to Russian territorial waters sounds like a bad deal for Norway. This thesis has given some reasons why this may not be the case, or at least not as bad as it appears on first sight. It has been shown that a distribution where each agent's share of both age classes is similar gives the best management of the stock. Today, the spawning migration takes place in Norwegian territorial waters. This means that Norway has greater access to the mature stock than Russia. The findings of this thesis therefore gives reason to expect an overall improvement to the efficiency of the fishery and hence greater steady state biomass. This will benefit Norway as well as Russia.

In addition to this effect, Norway may benefit from Russia being incentivized to harvest more mature fish and less immature fish. In the model explored here, this happens because harvest is linear in the stock and there is no biomass growth between the immature and mature stages. These factors in combination imply that shifting harvest towards mature fish leads to lower total harvest, giving a larger spawning stock and therefore greater recruitment. This mechanism may not be entirely realistic as it relies on some rather specific assumptions of the model, but the result may still be relevant. One important factor that this model does not capture is growth overfishing, which means fish are harvested inefficiently young while they still have a lot of growth potential. This problem arises because the growth is going to benefit everyone, but each agent will only take their own benefit into account, leading to too many immature fish being harvested. It seems reasonable to expect that owning a larger share of the mature age class would cause Russia to reduce growth overfishing as a larger share of the costs would also be born by them. This could then produce a similar result to the one found here.

If one thinks of stock levels and harvest in this model in terms of numbers of fish instead of biomass, the link between growth overfishing and the result described above becomes clearer. With this interpretation, a higher p^R leads Russia to harvest a lower number of fish rather than a lower biomass. This is precisely the point of catching mature rather than immature fish, as harvesting the mature fish provides more biomass per fish caught (or in this model, higher utility). This enables a larger catch (higher utility) while still allowing more fish to reproduce, leading to higher steady state stock levels.

This thesis has therefore provided two arguments why Russia getting increased ownership of the mature age class could make Norway better off. Hannesson (2006) also reaches a similar conclusion, despite using a very different model. There is therefore reason to expect that this scenario would not be as bad for Norway as one might expect.

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